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Assessing Constraints on Soldier Cognitive and Perceptual Motor Performance During Vehicle Motion

by Jason S. Metcalfe, James A. Davis, Jr., Richard A. Tauson, and Kaleb McDowell

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Assessing Constraints on Soldier Cognitive and Perceptual Motor Performance During Vehicle Motion

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14. ABSTRACT

Among the most significant challenges to implementing U.S. Army future force concepts are persistent human factors issues associated with staffing ground vehicles that are equipped with advanced capabilities including intelligent automation. This review is particularly concerned with understanding the influence of vehicle motion on the ability of Soldiers to perform goal-directed behaviors in future military vehicles. Because vehicle motion is a primary influence on the Soldier's performance, understanding the relationship between vehicle motion and performance is considered essential to solving the human factors problems brought about by implementation of advanced technologies in modern tactical vehicles. The review is organized in three main sections. First, a conceptual framework, alternately known as a "systems perspective," is introduced as a way to analyze the problem of Soldier-vehicle performance in terms of delineating the constraints that influence goal-directed behavior within the military context. Second, this framework is then used to structure an overview of research on whole-body motion and human performance, with a particular emphasis on relationships that have most frequently been identified in empirical studies. In the third and final section, the available information is applied to the military context in specific reference to lessons learned from the formal studies, field tests, and demonstrations that have been conducted with experimental platforms such as the Bradley infantry fighting vehicle and the crew integration and automation test bed (CAT). Overall, the extant literature taken in the context of direct observations in military platforms leaves little doubt that occupation of moving vehicles will result in detriments to performance of essential tasks for vehicle control as well as other essential command and control functions such as target acquisition, route planning, and teleoperation of remote assets. It is suggested that continued research and development efforts will benefit greatly from formalization of a unified framework for understanding the complex interactions between the constraints affecting survivability and lethality of future Soldier-vehicle systems. Ideally, such a formalized framework would lead to the development of formal predictive models that lend to the identification of a central set of principles to guide progressive design decisions aimed at optimizing overall system performance.

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1. Introduction

1.1 Problem Statement

U.S. Army future force concepts rely heavily on relatively small, lightweight and rapidly deployable manned and unmanned ground vehicles. Concomitantly, current plans to conduct operations with significantly reduced crews in manned platforms will require the combat Soldier of the future to adopt a dramatically different role involving concurrent monitoring and execution of a variety of tasks ranging from basic vehicle mobility to complex, on-line decision making. Moreover, owing to persistent and increasing security threats from highly adaptable enemies, future force designs are based largely on the concept of vehicles that are completely enclosed in armor (i.e., "buttoned up"). Therefore, in order to execute most in-vehicle tasks, Soldiers will be required to interact with a variety of computerized control and visualization systems that are designed to facilitate maintenance of situational awareness. As the role of in-vehicle Soldiers is progressively redefined in terms of evolving future force concepts such as these, so are the challenges to the ultimate implementation of battle-ready systems that are intended to preserve, if not enhance, lethality and survivability (Speakes & Martin, 2008). Among the most significant challenges are persistent human factors issues associated with manning ground vehicles that are equipped with advanced C3I[2] capabilities, including intelligent automation. Of particular concern are potential decrements in the performance of the physical and mental tasks required to successfully achieve mission objectives from within a moving vehicle (McDowell et al., 2007). The aim of the current review, therefore, is to highlight what is known about the influence of a whole-body motion on human performance and to assess how this knowledge should provide the basis for plans regarding the optimization of the design of manned ground vehicles to enhance Soldier performance during vehicle motion.

1.2 Background

Outfitted with high-powered visualization and computing, broadband mobile networking, robotics and artificial intelligence, as well as a variety of other evolving technologies, future U.S. Army vehicles represent a radical conceptual shift in allocation and use of resources. Not only have future force concepts led to expanded capabilities of tactical vehicles, but they have also transformed the vision of the Soldier and his or her role in mobile operations. Whereas vehicle operators of the past have been able to focus on a somewhat restricted set of tasks, such as those associated with manual driving, designs of future vehicles will tax the operator's ability to a much greater extent (Sterling, Perala, & Blaske, 2007; Sterling & Burns, 2003; Sterling & Perala, 2007). Examples of added task demands include the potential for concurrent monitoring of unattended

[2] Command, Control, Communications, and Intelligence; here, the C3I designation is used as a general shorthand for C4ISTAR which, in addition to the C3I, includes Computers, Surveillance, Target Acquisition and Reconnaissance.

ground sensors (UGSs), maintenance of communications with dismounted troops and other vehicles, route planning and operation of unmanned assets (unmanned ground vehicles, and unmanned aerial vehicles), operation of non-line-of-sight (NLOS) munitions, as well as maintenance of supervisory control over the vehicle within which the Soldier is operating. Although progress in science and engineering has led to significant advances in the capabilities of tactical military vehicles, a variety of human performance issues has been brought to the fore as a result of current technical solutions for meeting advanced automation needs (Stanton & Marsden, 1997; Stanton & Young, 1998; Sterling & Burns, 2003). Among the problems induced by staffing advanced vehicle systems are biomechanical (Sirouspour & Salcudean, 2003; Sövényi & Gillespie, 2007), cognitive (Parasuraman & Riley, 1997), and psychomotor (Stanton & Marsden, 1997; Stanton & Young, 1998) issues that will negatively affect execution of mission-critical functions. Several factors have been identified as important determinants of the amount and type of performance decrements that will result, including the limited field of view (FOV) brought about by indirect vision systems (e.g., cameras used to see the forward view of the vehicle as opposed to Soldiers looking through vision blocks or an open hatch), time lags in the system control loop, suboptimal characteristics of the steering input device for vehicle control, and finally, physical effects of vehicle motion on the operator (McDowell et al., 2007). Without improvement, the fundamental issue of degraded human performance as a function of these and other factors will compromise achievement of future force objectives.

Central to each of the issues mentioned is the performance of the Soldier. Whether because of a limited FOV or a suboptimally tuned steering system, the ultimate realization of design problems will be the degraded ability of the Soldier to meet his or her task goals. Vehicle motion is a primary influence on the Soldier's performance. Therefore, understanding the relationship between vehicle motion and performance is essential to solving the human factors problems brought about by implementation of advanced technologies in modern tactical vehicles. Delineating and understanding the influences on human performance inside military vehicles, however, is no trivial matter. Even in the context of civilian driving, understanding how vehicle motion impacts performance is a complex task (Treffner et al., 2002). This issue has been studied indirectly through the assessment of the effects of whole-body motion on human cognitive, perceptual, and motor behavior in literally hundreds of studies (see the following for reviews: Conway et al., 2007; Grether, 1971b; Griffin, 1990; Griffin & Lewis, 1978; Kjellberg & Wikström, 1985; Lewis & Griffin, 1978; McLeod & Griffin, 1989). Despite these and other considerable efforts at disentangling the relationships between the characteristics of whole-body motion and human performance, significant questions persist. These questions are particularly salient when one is attempting to transition knowledge gleaned from controlled laboratory studies of whole-body motion to an understanding of performance in particular environments such as tactical military vehicles.

Although a vast array of data exists regarding the relationship between whole-body motion and performance, few attempts have been made to integrate the empirical literature into a single

conceptual framework or model. There have been, of course, noteworthy exceptions based on studies of whole-body vibration and manual performance (c.f., Lewis & Griffin, 1978; McLeod & Griffin, 1989); however, to our knowledge, no attempts have been made to formalize these heuristic models nor have any empirical tests been designed to assess their validity. The existence of such a validated framework, however, would be valuable for designers and engineers because of its potential to provide a set of concepts to guide attempts at optimizing Soldier-vehicle system performance. In order to develop such a framework, it is critical to begin by organizing what is known about qualitative aspects of global and specific influences on human performance while subjected to whole-body motion according to a common set of concepts. Therefore, the purpose of the current review is to present a synthesized overview of extant data regarding the influence of whole-body motion on human performance in order to facilitate the formulation of a framework for assessing performance in military vehicles and further, to provide concepts that may be used to guide design modifications to optimize system performance. The review is thus organized in three main sections. First, we introduce a conceptual framework that has proved valuable for studies of human cognitive and perceptual motor behavior in other scholarly domains and may therefore shed light in the current domain of interest regarding behavior in vehicles. Second, we use this framework to structure an overview of research on whole-body motion and human performance. Given the extent and breadth of the available information, we only present highlights from the relevant literature focusing on relationships that have appeared most frequently. Of course, by limiting our focus to the most frequently observed findings, we assume that they provide the most reliable information upon which future proposals for design modifications can be based. Accordingly, in the third and final section, we apply the available information to the military context. Specifically, we aim to initiate the development of a synthesized, predictive understanding of how vehicle motion will influence Soldier performance and further, to assess design solutions that may mitigate the consequences of having to perform complex tasks during mobile operations in tactical military vehicles.

2. Analysis of Human Performance in Complex Environments

This review is concerned with understanding the influence of vehicle motion on the performance of goal-directed behaviors in military vehicles. Goal-directed behaviors are distinguished from other aspects of human behavior, such as basic physiologic functioning, in that they are associated with a consequence(s) that the operator intends to bring about. The organization of any goal-directed action is complicated and to understand it requires an analysis of an incredibly high-dimensional, dynamic system (see Turvey et al., 1982, for extended discussion). That is, when we consider all the individual elements that comprise the body of a person (e.g., neural systems, muscles, joints) as well as the variety of possible circumstances presented by a dynamic task environment, the number of choices and control options even for an act as simple as toggling a

switch approaches infinity. Recently, scholars have made significant progress in understanding human behavior by drawing an analogy between the complexity inherent in cognitive and perceptual motor actions to that seen in chaotic dynamical systems (Kelso, 1995; Kugler et al., 1982). From this so-called "systems perspective" has come the notion that although structure and predictability can be observed in behavior, understanding dynamic influences on performance requires more than cataloging results from targeted empirical studies. To access the bigger, synthesized picture of performance in a particular context, one must understand the variety of factors that delimit the behavioral options within that context (Newell, 1986; Pattee, 1976, 1988). The role of targeted empirical studies is paramount since individual observations are the foundation upon which an understanding of the whole will be built. Eventually, however, findings must be organized into a coherent picture that will not necessarily be evident from continued focus on simple independent-dependent variable pairs.

Using a systems framework enables understanding through a relatively simple construct. That is, behavior is emergent from cooperative and competitive interactions among essential elements of the entire system, which include the operator as well as broader contextual factors (Kelso, 1995; Kugler et al., 1982; Newell, 1986). Further, no element of the system is intrinsically privileged with sole responsibility for the form of its behavior. Instead, in terms of the details of its appearance, behavior will be determined by a confluence of factors as the task unfolds. In other words, if any of the relevant variables (or constraints) affecting a behavior is changed, then one can expect a change in performance of that behavior. Importantly, because a systems framework considers behavior to be multiply determined (meaning that it is under the control of many constraints), it logically allows one to consider alternate solutions when problems are brought about by individual factors that are relatively impervious to improvement. In the case of the Soldier-vehicle system, this means that the effects of certain relatively uncontrollable variables, such as the layout and structure of the terrain, may be compensated through manipulation of other variables, such as properties of the interfaces the human uses to perform his or her tasks.

In the systems framework, the process of understanding a given behavior begins with the identification of its foundational constraints. A useful entry point involves consideration of constraints associated with the characteristics of the operator (organism), the environment, and the task to be performed (Newell, 1986). *Organism constraints* are derived from mechanical properties of the body as well as its functional capacity in terms of physiology and behavioral capabilities (e.g., cognitive, perceptual and motor abilities). In a similar fashion, *environmental constraints* are based on physical properties such as terrain, external forces (e.g., gravity, wind shear), and the support surface (e.g., seat), as well as informational content such as ambient light, noise, and presence of other personnel. *Task constraints* are derived from the requirements for successful performance. Thus, task constraints include abstractions such as those defined by task type (i.e., verbal, visual, motor, etc.), overall mission objectives and rules of engagement as well as more explicit physical factors such as those defined by the objects (e.g., levers, buttons, computer screens) with which the operator must interact in order to perform a goal-oriented action.

A simplified example of how one might begin outlining the task and environmental constraints associated with the Soldier-vehicle system is depicted in figure 1 (organism constraints and their interaction with task and environment are discussed in more detailed fashion in the following paragraph). As can be seen, environmental constraints are derived from factors inside and outside the vehicle. The primary source of environmental constraints affecting the Soldier is seen as defined by the vehicle and its motion characteristics, but at the same time and because that which affects the vehicle is likely to affect the Soldier, global environmental constraints are also seen as important. Similarly, physical task constraints are depicted as related to elements of the various interface devices that define the operational capabilities afforded the Soldier for command and control tasks, driving the vehicle that s/he is presently occupying or for remotely driving (i.e., teleoperating) another unmanned asset. Because physical realizations that can be illustrated were not available, task constraints associated with abstractions such as task type, mission objectives, and rules of engagement are not shown but are still considered as part of the overall Soldier-vehicle system. Certainly, these types of variables are equally important as are physical variables in terms of defining what behavior a Soldier is supposed to do, when s/he is supposed to do it, and how it should be done. A more inclusive list of possible constraints that interact to influence human cognitive and perceptual motor performance in military vehicles is provided shortly.

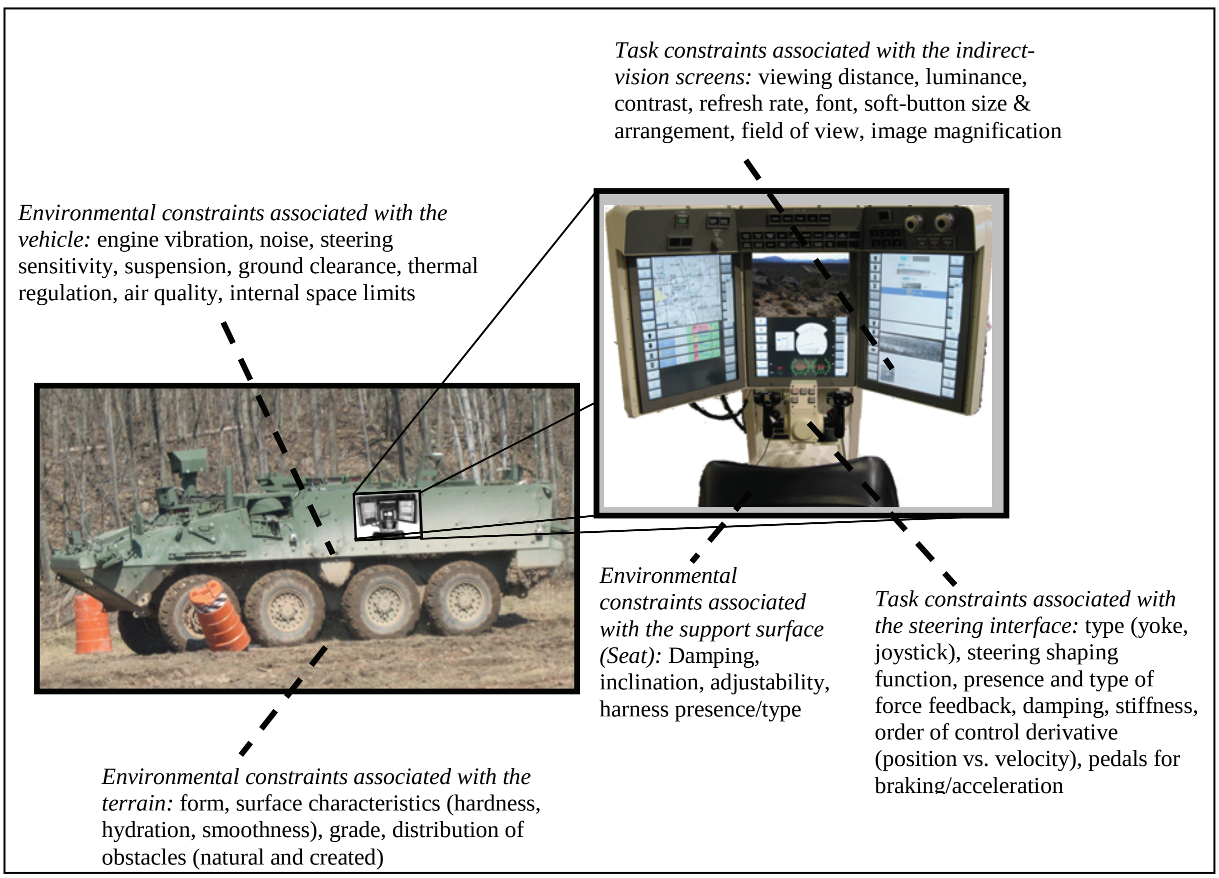

Figure 1. An example of identification of environmental and task constraints for the Soldier-vehicle system.

Figure 2 provides one possible representation of the organism constraints for a human performing cognitive, perceptual, and motor tasks. This taxonomic model, or heuristic, has been adapted from one presented in a review of continuous manual performance during whole-body vibration (Lewis & Griffin, 1978), and it organizes functional organism constraints into categories of essential perceptual, motor, and central processes. This heuristic represents important perceptual motor interactions that are known to exist and influence human performance. For instance, fundamental interactions among the various motor processes such as eye movement, limb action, and postural control have been verified through studies of human development (c.f., Bertenthal & von Hosten, 1998). At the same time, since Lewis and Griffin published their review, it has been revealed that these interactions are considerably more dynamic and complex than once thought. Thus, the heuristic has been re-arranged and directional arrowheads have been removed to reflect a modern understanding of human behavior. That is, rather than implying directionality of influence between components, the connections represented in figure 2 indicate fundamental couplings in behavioral control. For example, the relationship between posture and perceptual information is now viewed as a coupled or (integrated) sensorimotor loop wherein movement is controlled to affect perception as much as perception is used to control motion (Dijkstra, 2000; Reed, 1982). Likewise, whereas Lewis and Griffin proposed that the internal state (called "internal environment" in the original publication) only impinged on attention processes, we have given it a place at the top of the heuristic to represent its more diffuse influence over all aspects of behavior. Important to the current review, as can be seen in figure 2, our depiction of the internal state in this manner gives greater prominence to task and environmental constraints and indicates that they are in a prime location for affecting many aspects of Soldier performance as well as balancing one another's influence. This notion of broad effects of task and environmental variables is consistent with current concepts of human behavior as a product of an integrated "cognitive perceptual motor system" rather than resulting from organization among distinct "cognitive," "perceptual," and "motor" modules (Beer, 2000; Middleton & Strick, 2000).

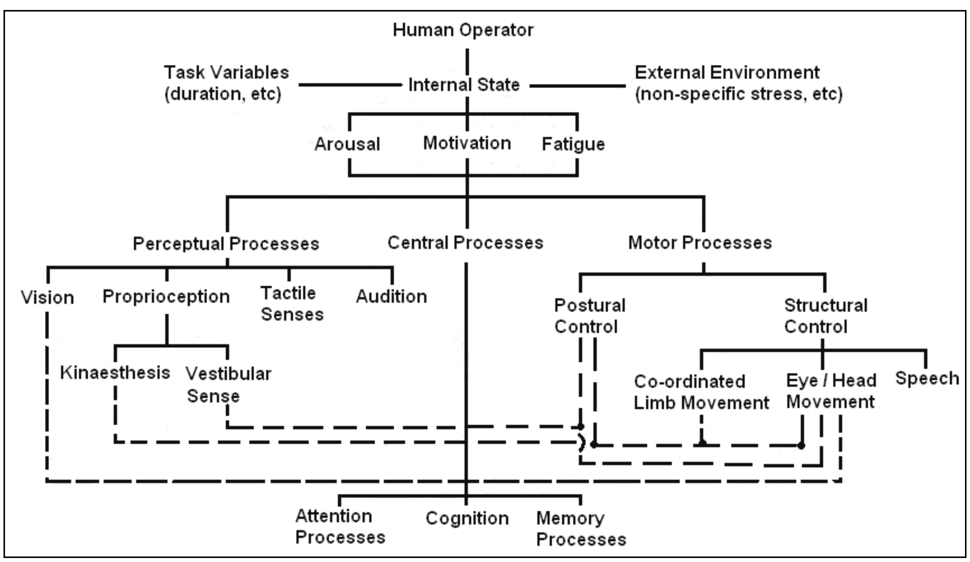

Figure 2. One depiction of key functional organism constraints on human cognitive and perceptual motor performance based on a similar heuristic initially presented by Lewis and Griffin (1978).

To begin our analysis of the effects of vehicle motion on performance, we have organized the constraints on the Soldier-vehicle system as shown in table 1. To date, most research on the influence of a whole-body motion on human performance has focused primarily on vibratory motion and its effects on visual acuity (usually measured by reading errors) and manual performance (measured primarily in tracking tasks), although other aspects of behavior have been studied (i.e., memory, reaction time, workload, etc.). In addition, most past research has assessed the relationship between behavior and particular environmental constraints such as vibration frequency, amplitude, and duration, with only occasional examination of other constraints (i.e., noise, ambient temperature, etc.) and their interactions (e.g., Grether et al., 1971). There are other considerable bodies of research on whole-body motion in humans (e.g., on the subjective experience of vibratory motion) (c.f., Hacaambwa & Giacomin, 2007; Ingre et al., 2006; Mansfield et al., 2000; Oborne & Boarer, 1982a, 1982b) and the influence of sustained acceleration (c.f., Albery, 1989, 2004; Grether, 1971a). However, because of the experimental conditions used and variables reported, much of this other literature is less directly applicable to the issue of Soldier performance in tactical military ground vehicles. Despite this generalized lack of relevance, some insights may be drawn from these other bodies of research, and we will certainly use any available information to speak about relevant issues. Therefore, the current presentation focuses on the relationships between whole-body motion and performance of tasks representative of those faced by Soldiers in future force vehicles (most frequently, these will be discrete and continuous manual tasks) while incorporating discussion of information regarding the less-studied constraints listed in table 1 when it is available and relevant.

Table 1. Summary of relevant constraints for the Soldier-vehicle system.

Organism	Environment	Task
Structural constraints • body mass • body composition • segment lengths and proportions **Functional constraints** • internal state: arousal, motivation, fatigue • sensory-perceptual capabilities: vision, proprioception, tactile, auditory, vestibular, kinaesthesis • processing speed: neural conduction, reaction time, detection time • musculo-skeletal properties: movement speed, coordination, strength, power, precision, accuracy, postural control • cognitive capabilities: reading speed, comprehension, quantitative reasoning, language ability, memory, attention	**Physical environment** • support surface: seat, damping, stiffness, availability and type of postural support (backrest, harness, armrest) • motion: frequency content, amplitude, direction, duration • thermal conditions • air quality (flow, smell, humidity) **Informational content** • visual array: luminance, layout, viewing distances, relative motion (parallax), field of view, contrast, texture • auditory: vehicle noise, communications from other personnel (intra- or extra-vehicular) • psychological stressors	**Physical requirements** • object type: lever, button, knob, toggle • object properties: shape, size, stiffness, damping, location • availability of feedback (e.g., controller force feedback) **Mental requirements** • decisions: number of choices, contingencies, etc. • presence of distractions • memory demands: recognition vs. recall • attention: number of separate foci for attention **Abstractions** • goals: force, speed, accuracy • rules, objectives, orders • time requirements

The purpose of this review is to use the systems framework to synthesize what is known about the influence of whole-body motion on human performance and then to apply this knowledge to military vehicles. Thus, the remaining discussion is organized in two parts. The first is intended to provide an integrative discussion of the main constraints influencing the behavior of the Soldier-vehicle system. Although not exhaustive, this is a broad overview of the most relevant literature; much of the focus is on summarizing and synthesizing the most extensive area of research, that is, studies focusing on the influence of whole-body vibration. To provide an overall context, this first section begins with an overview of the limited number of studies that have identified performance decrements in military platforms. In the second section, we turn our attention to known and possible applications to U.S. Army future force vehicles. Opening with a discussion of the constraints that may provide the most opportunity for improving system performance, this section concludes with explicit examples of implementations that have been tested in current experimental military vehicles and how they have affected in-vehicle performance during relatively controlled circumstances.

3. Summary of Relevant Literature

3.1 In-Vehicle Observations

A number of studies suggest that Soldiers in tactical vehicles will suffer performance decrements during military operations (Nakashima & Cheung, 2006). For example, Soldiers in a visually isolated, tracked, moving vehicle (the U.S. Army command and control vehicle [C2V]) demonstrated reduced cognitive and fine motor performance while completing a battery of computer-based tasks (Cowings et al., 2001). A variety of measures, including motion sickness, psychomotor performance, and physiological variables, was examined over periods of occupation spanning 4 hours, including epochs during which the vehicle was stationary or moving. Experimenters concluded that occupation of the moving C2V had a significant impact on performance. Decrements on individual subtests were as large as 20% below baseline measures recorded in a classroom outside the vehicle. On average, however, the difference between occupying the moving versus a stationary C2V was only on the order of ~3% to 7%, whereas a decrement of ~3% to 8% was observed for occupation of the vehicle as compared with performance in a classroom environment. Therefore, one could reasonably estimate that the performance effect of occupying a moving C2V as compared with a classroom-type environment was between 6% and 15%, depending on the performance measure of interest. Assessment of specific results was also revealing. For example, with motor variables such as choice reaction time and repetitive finger tapping, 5% decrement was observed, whereas cognitive performance appeared to degrade between 10% and 15%. It is worthwhile noting that cognitive assessments required motor responses, and thus, one may conclude that the observed decrements reflected cumulative effects on cognitive performance, including motor decrements, rather than on cognitive performance in

isolation. To provide additional context, Cowings et al. converted the performance scores to an equivalency in terms of blood alcohol content (BAC). In this, performance levels of 8 of 23 subjects were identified as equivalent to or worse than the performance level of a person legally impaired at the 0.08% BAC level, and 19 of 23 subjects were impaired equivalent to a 0.025% level, which was considered the minimum BAC where observable performance decrements would appear. In similar research with 18 military participants who completed cognitive tests from inside a modified M113 armored personnel carrier, the stressors associated with vehicle motion were related to degraded performance of cognitive tests (Schipani et al., 1998). Increasing the degree of vehicle motion led to an increase in the percent of incorrect responses and time necessary to complete the tests. The findings from these more recent studies were consistent with earlier works which found that sustained enclosure in a moving vehicle was associated with losses in stamina, gross motor coordination, and equilibrium; moreover, the functional effects were apparently compounded by physical symptoms including cramps, nausea, backache, indigestion, soreness of the neck and extremities, headache, and dizziness (Hicks, 1960; Lewis, 1962).

In addition to the effects on physical and cognitive performance, considerable research and colloquial experience has indicated a high probability that motion sickness will result from operation within military vehicles. Motion sickness is a generalized descriptor of a variety of symptoms including drowsiness, sweating, nausea, and vomiting resulting from real or perceived motion (Bittner & Guignard, 1985). In one study, 73% of the participants reported moderate to severe symptoms common to motion sickness after two relatively brief (20-minute) exposures in an amphibious assault vehicle (Rickert, 2000). Similarly, in another study of participants tasked with completing a simulated driving task while in the back of a high mobility multi-purpose wheeled vehicle (HMMWV), nearly 40% of those who experienced vehicle motion reported moderate to severe symptoms (Hill et al., 2004). This contrasts with only ~15% of the participants reporting similar symptoms despite the vehicle remaining stationary. In the previously discussed study within the C2V, more than 50% of the participants reported moderate to severe levels of motion sickness (Cowings et al., 2001). Taken together, these observations indicate that some operators can be expected to experience motion sickness symptoms when operating tactical vehicles. Moreover, although not a universally accepted claim, it has been argued that increased exposure to motion sickness symptoms is associated with reduced motivation and this leads to reduced work rate, disruption, and sometimes the complete abandonment of work (Bles et al., 1998). As an example of how severely performance may be impacted in certain cases, Tauson et al. (1995) noted that during a test where participants completed cognitive tests in a Bradley infantry fighting vehicle (IFV), one person was effectively incapacitated (e.g., lost consciousness) because of motion sickness during traversal of a sandy stream bed at 10 mph.

Performance degradations that have been observed in military vehicles are further supported by laboratory studies that have demonstrated that movement can influence specific aspects of task performance. That is, vibration can degrade sensory input (Griffin, 1990; Moseley & Griffin, 1986); physical perturbations and visual distortions can degrade movement control (Contreras-

Vidal & Kerick, 2004; McDowell et al., 2005; Rider et al., 2003); motion sickness can globally change the person's state (Bittner & Guignard, 1985), and postural instability can change central nervous system processing (Redfern et al., 2002). Laboratory studies also suggest that vehicle enclosure can lead to motion sickness and performance degradations. Operating in a moving vehicle creates a situation defined, in part, by sensory mismatch. Such sensory mismatches have been shown to degrade human performance even when the discrepant sensory input is made explicit to the performer (Contreras-Vidal & Kerick, 2004). One explanation for this is that such degradations are caused by a lack of redundant information, which can be used to reduce system noise and to bias integration of sensory input (Erlhagen & Schöner, 2003; Kagerer et al., 1997). Discrepancies between the sensory systems or in the estimation of earth reference are also believed to be causally related to symptoms within the motion sickness family (Bos & Bles, 1998; Oman, 1991; Reason & Brand, 1975). Whether air, car, sea, space, or simulator sickness, cybersickness, clinical vertigo, or Sopite Syndrome, associated symptoms are the potentially debilitating side effects of actual and perceived vehicle motion. However, relationships between motion sickness and performance have yet to be clearly identified because of the large inter-individual variability in terms of susceptibility (Stanney et al., 1998) and the varied symptomatology across different members of the motion sickness family (air, car, simulator, etc.) corresponding to different modes of motion that may induce their effects.

For those Soldiers tasked with teleoperation of robotic assets or unmanned vehicles (UVs), performance degradations associated with vehicle motion may be aggravated by additional uncorrelated sensory information from the asset or UV. Vehicle teleoperation is defined as the driving of a vehicle from a distance away from the vehicle itself (Fong & Thorpe, 2001). Unlike remote driving through direct vision of the vehicle in its environment, teleoperation requires transmission of sensor data (from cameras, global positioning system, sonar, etc.) relating local vehicle information to facilitate or simulate a first-person experience of occupying the vehicle being driven ("telepresence"). When one is teleoperating from within a moving vehicle, the expectation of exaggerated performance effects resulting from vehicle motion for UV pilots/drivers is attributable to the known disparity between the motion of the UV and the motion of the vehicle in which the Soldier is traveling. Because humans depend on redundant sensory information to facilitate interpretation of their environment, uncorrelated sensory information from different motion environments (such as riding in one vehicle but driving another) may have undesirable effects. For example, in one study, participants experienced three different motion environments: one created by the motion of a ship, one created by a flight simulator, and one created by the combined motion of the ship and a flight simulator (Muth & Lawson, 2003). It was found that combination of ship motion and the flight simulator reduced dynamic visual acuity more than the ship motion or the flight simulator alone. In an ensuing study with a ground vehicle, Muth and colleagues showed reductions in accuracy and increased time to complete a simulated teleoperation-type task when riding in a vehicle driven by another person (Muth et al., 2006). This represents a critical problem since future force concepts have, at their foundation, the notion of off-

loading hazardous tasks to UVs that are to be teleoperated by Soldiers in remote locations; often, the remote locations are other vehicles.

It is clear that significant effects of vehicle motion on human performance are to be expected in cognitive, visual, and manual tasks (Nakashima & Cheung, 2006). In general, performance decrements on the order of 5% to 15% have been observed as compared with similar tasks performed outside a vehicle in stationary environments. The effects appear complex; for example, certain performance decrements are observed in a vehicle, regardless whether that vehicle is in motion. Yet the effects of motion can be accounted for at a number of levels of precision. Consider the expected decrement in a movement task requiring a Soldier to respond to a visual stimulus from among an array of three highly distinct options, perhaps in a scenario involving control of multiple NLOS weapons based on information provided by an array of UGS systems. Simple human reaction time takes a minimum of 200 milliseconds (ms), and depending on the specific task and conditions, additional choices can increase that reaction time to 500 to 800 ms or longer (c.f., Hyman, 1953). If average reaction time in a given task is 650 ms, for example, then an expected 7% decrement would cause an additional delay of 45.5 ms. Although this decrement may appear small, consider that reaction time is merely the time between stimulus detection and the *initiation* of a particular response. In other words, the difference of 45.5 ms before initiation of the movement may only be the ephemeral "tip of the iceberg" in a chain of decrements since there would likely be concomitant increases in movement execution time with increased vehicle motion. If, for example, it could be determined that the same task suffered a 10% reduction in accuracy when the vehicle was moving, it could be inferred that a trained operator might be inclined to slow his or her execution of the action to reduce the likelihood of performing the task in error. Because there is a known trade-off between speed of task execution and level of accuracy (Plamondon & Alimi, 1997), additional time would be required to successfully complete the prescribed task. In some cases, this additional time may be the difference between (for instance) hitting or missing a target of opportunity. Although such information would be useful to developmental efforts for future force initiatives, further research and review are necessary regarding the mechanistic relations between various aspects of Soldier performance and characteristics of whole-body motion as would be induced by operation in a military vehicle.

3.2 The Effects of Whole-Body Motion on Performance

3.2.1 Organism Constraints

First and foremost, the human body is a physical entity. Thus, the passive response of the body to force input will always be a function of (a) its own mechanical properties and (b) its state of motion when the force is imposed. Information regarding these two factors may enable straightforward predictions of how a body will respond to a particular input, provided all necessary initial conditions are known with certainty. At the same time, determining all necessary conditions to facilitate prediction of the effect of applying a given force to a given human is usually not as simple as the application of standard equations of rigid body mechanics. Without a doubt, if

one is willing to assume that rigid body mechanics apply to the human within a reasonable error tolerance, approximations can be made. However, because the human body is made of deformable (viscoelastic) materials and because it has a structure that is articulated in literally hundreds of joints, standard mechanical equations are only likely to provide rough estimates of how a body will actually respond to a given force. Moreover, the human body is decidedly not a passive mechanical entity. Because humans have the ability to actively control force-producing tissues (their muscles), they literally have the ability to manipulate those parameters (such as stiffness) that dictate how an imposed force would affect it (Enoka, 2002; Loram & Lakie, 2002; Winter et al., 2001). Therefore, although it is useful to obtain reasonable estimates of the passive physical inertial parameters of the body that describe how (with no active response) a body will respond to a given force, this knowledge alone cannot provide an understanding of how whole-body motion will influence behavior.

Although some have published values for resonance frequencies of various body parts (e.g., Duarte & Pereira, 2006), meaning those frequencies where the body shows the greatest response to a force input, others have considered the variables of transmissibility, energy absorption (or absorbed power), apparent mass, and impedance to be more indicative of how the body will respond to a given vibration in a given context (Holmlund & Lundström, 1998; Lundström, Holmlund, & Lindberg, 1998; Matsumoto & Griffin, 1998; Paddan & Griffin, 1998). In general, this latter group of measures bases analyses on empirical measurements of the motion input as well as the kinematics of the resulting body motion, thus accounting for any filtering-type effects that the body has on force input. For example, transmissibility has been estimated as the ratio of the relative amplitude of body motion to vibration input, whereas apparent mass has been calculated as the input force divided by resulting body acceleration. In most cases, measures such as these that assess the relationship between input to the body of a seated person and the resultant whole-body motion have found the greatest physical responses at or near 5 Hz for vertical frequencies and at or near 1 to 2 Hz for horizontal (lateral or fore-aft) frequencies (Holmlund & Lundström, 1998; Lundström & Holmlund, 1998; Mansfield et al., 2000; Mansfield & Griffin, 1998; Matsumoto & Griffin, 1998). In some of these studies (Holmlund & Lundström, 1998; Paddan & Griffin, 1998), additional "peak frequencies" have been observed in one or both of the horizontal directions, which were not observed in the vertical, and this observation was attributed to an influence of individual body segment resonances (head, arms) superimposed on the primary whole-body response that is assumed to be characterized by the first, lower frequency peak. Please note that there is considerable intra-individual variability in these estimates that is presumably attributable to differential morphological characteristics and other functional factors (e.g., strength, endurance, etc.) as well as variability because of differences in other sources of constraint such as environmental characteristics and task requirements (Paddan & Griffin, 1998).

Although a measure of the basic physical response of the body to vibration, excluding the influence of task constraints, the frequencies of whole-body resonance are important inasmuch as they appear to be related to many of the overall behavioral effects that have been observed. However,

other, more specific effects have been observed for which knowledge of the physical parameters of individual body segments may be of value. Although less information is currently available to characterize a broad spectrum of individuals across variations in race, gender, and age, some values have been published to provide at least a reference for the general order of magnitude. Table 2 provides some of these values, indicating resonance frequencies for individual upper body segments as published by Duarte and Pereira (2006). Note the general relationship between body segment size and the resonant frequency. As should be expected, segments that tend to have greater mass also have lower resonant frequencies. Of course, as with the measures of whole-body motion in response to vibration, these values should be treated as approximations; for example, others have reported the resonance of the spine as closer to 5 Hz rather than 8 Hz as shown in table 2 (Matsumoto & Griffin, 1998).

Table 2. Resonances of individual segments and organs of the upper body. (The table is adapted from Duarte & Pereira [2006, p. 369].)

Body Segment/Organ	Resonance Frequency (Hz)
Head	20 to 40
Spinal column	8
Chest wall	60
Abdomen	4 to 8
Shoulders	4 to 8
Lungs	4 to 8
Hands and arms	20 to 70
Eyeball	60 to 90
Upper jaw	100 to 200

3.2.2 Environmental Constraints

The environment of the Soldier will be defined by his or her surroundings immediately within the vehicle. Likewise, the environmental constraints provided by the vehicle will largely be governed by the characteristics of its surroundings, particularly the terrain it traverses and global factors such as the weather. However, it is the interaction between surface properties, such as ground texture (smoothness/roughness) and grade, with the design of the vehicle (tire type, suspension) that will be the primary influence on the motion that the operator will experience (Bianchi, 2007). Although the influence of terrain over vehicle motion will be, from the operator's perspective, relatively random and only weakly predictable, attempts at understanding how vehicle motion may affect performance must first begin with more controlled scenarios. Accordingly, a vast majority of research to date has been performed with single-axis vibrations or accelerations across a discrete range of "pure" motion characteristics such as at a constant single frequency, amplitude, or acceleration. For studies of whole-body vibration, experiments have typically been conducted on individuals who are seated on some type of "shake table" or other platform for inducing controlled whole-body oscillations.

Studies of whole-body acceleration, on the other hand, have been performed on individuals seated in "human centrifuges"; these latter studies commonly assessed performance during conditions more representative of aerial than terrestrial navigation and thus have less bearing on this review. In

general, the overall finding is that whole-body motion causes significant degradations in human performance across a range of cognitive, perceptual, and motor tasks (Conway et al., 2007; Griffin, 1990), and the array of effects is broad and complex. Typically, to understand how whole-body motion affects performance requires consideration of specific properties of the environmentally induced forcing function such as frequency, amplitude, direction, and duration (Kjellberg & Wikström, 1985; Lundström et al., 1998; Mansfield & Griffin, 1998). Moreover, whether decrements occur and if so, how they are manifest, will be a product of environmental input and a function of task constraints.

Regardless of task type, when performance decrements have been observed, the pattern of influence has most often been characterized by a frequency of maximum decrement along with changes mitigated by amplitude and direction of the motion input. For example, several reviews have indicated that errors in manual tracking performance tend to peak at relatively low disturbance frequencies (between 1 and 5 Hz) with enhanced performance as disturbance assumes higher or lower frequency characteristics (Griffin, 1990; Lewis & Griffin, 1978; McLeod & Griffin, 1989). Similarly, at short viewing distances, the relationship between vibration and visual acuity shows maximum detriment at or near 5 Hz, but this value increases to ~10 to 25 Hz as viewing distance increases beyond a couple of meters (Griffin & Lewis, 1978), possibly indicating that different body resonances dictate acuity effects at different viewing distances (e.g., trunk/spine resonance at short distances and head/eye resonance at longer distances).

Generally speaking, when frequency is held constant and the amplitude of the disturbance is increased, performance errors also tend to increase (Mansfield & Griffin, 1998; McLeod & Griffin, 1989); this suggests that this increase is exaggerated at lower frequencies (Grether, 1971b). Consistent with the current trend of relating the effects of whole-body motion to variables such as impedance and absorbed power, the early suggestion as to how these environmental constraints affect performance was that detriments are directly and nearly linearly related to the amount of energy in the disturbance (Buckhout, 1964). If this is the case, then the disproportional influence of amplitude at lower frequencies may be explained by the greater velocity of disturbance sustained over a larger range of displacement. To further complicate articulation of a precise understanding of how the properties of whole-body motion relate to human performance, the duration of the exposure must be considered. As with most other constraints, there is no direct formula that indicates how an exposure of a given duration will influence the performance of a given task. For many variables, there seems to be a small-to-moderate but significant detrimental influence of prolonged exposure on physical aspects of performance that is most likely related to factors such as fatigue (c.f., McLeod & Griffin, 1993). At the same time, some tasks, such as those that require sustained vigilance, show the opposite trend and benefit from extended exposure to low levels of vibration (Kjellberg & Wikström, 1985).

Overall, the impact of whole-body motion on human performance has been validated in vehicles and in laboratory studies. Laboratory studies, in particular, have provided a wealth of data that allow specification of particular effects based upon motion characteristics such as frequency,

amplitude, direction, and duration. Some of these effects, such as the influence of frequency and amplitude, may be understood in a general way as presented. That is, there appears to be a clear relationship wherein performance degradation shows a peak at particular frequencies (or within certain frequency ranges), and the expected amount of degradation increases as the amplitude of the disturbance increases. However, to understand the performance effects in more specific fashion, such as which frequencies produce the most detriments and during what circumstances, and to understand more complex relationships, such as the influence of direction and duration of exposure, we need to assess results as a function of the characteristics of the tasks to be performed.

3.2.3 Task Constraints

In his ecological approach to human perceptual motor behavior, Gibson (1979) argued that the task defines the essential interactions between the operator and the environment (e.g., the interactions between an organism and environmental constraints). In other words, this implies that in order to understand why a particular person manifests a particular behavior in particular circumstances, one should understand the relationship between the organism and environment in light of the constraints imposed by the task (Newell, 1986). Consider, for example, the observation that vertical whole-body vibrations at frequencies around 5 Hz appear related to the greatest amount of performance errors in manual tracking tasks, particularly when the tracking involves coincidental operation of a lever in the fore-aft direction (the *y*-axis). Given the additional information that, for the average human adult, the resonance and maximal transmissibility/power absorption of the body occurs around this same frequency for vertical vibrations (Mansfield & Griffin, 1998; Paddan & Griffin, 1998) and further, that this has been repeatedly identified as the vertical resonance of the spine (Matsumoto & Griffin, 1998), it should be of little surprise that tasks involving motion along a coincidental axis would be affected at this common frequency.

To go a step further, if one wanted to mitigate the expected influence of a vibration in the fore-aft direction in the scenario described, then the task constraints should be structured to eliminate, accommodate, or compensate confounds with the vertical direction of disturbance, at least for frequencies at or near 5 Hz. This concept has received considerable recognition since, for instance, the influence of the direction of whole-body motion has most commonly been observed as the greatest in the direction that the task is to be performed; that is, lateral vibrations and accelerations have had most influence on lateral tracking and both fore-aft, and vertical disturbances have had the most influence over fore-aft tracking (Grether, 1971b; Lewis & Griffin, 1978; McLeod & Griffin, 1989). Of course, real-world motion will rarely, if ever, be restricted to a single direction, amplitude, and/or frequency. Of the studies that have examined the influence of multi-axis or mixed frequency motion, a similar pattern of results has been observed as that seen in single-frequency/single-axis studies. Specifically, extant data regarding manual performance have indicated a peak disturbance frequency around 5 Hz even with pseudo-random stimuli. Overall, the net influence of more complex disruptions appears to be related to the resultant direction, amplitude, and frequency content rather than dominated by motion characteristics in any particular axis or frequency band (Albery, 2004; McLeod & Griffin, 1989).

As with direction, other task factors can be related to variations in the results observed across studies. For example, assessment of research in the use of a joystick controller reveals a subtle interaction between task constraints and the pattern of influence of whole-body motion. It appears as if the effect of frequency (a rate variable) tends to be most robustly observed when the operator is performing tasks involving first order (rate-based) control, whereas the effects of amplitude are most clearly seen during performance of zero order (amplitude-based) control tasks (Lewis & Griffin, 1978; McLeod & Griffin, 1989). Differences have also been seen in the effect of whole-body motion as a function of task type. For example, based on a meta-analysis, Conway and colleagues concluded that imposed motion affected perceptual motor tasks nearly 2 to 3 times as much as cognitive tasks (Conway et al., 2007). Conway et al also noted that tasks emphasizing speed tended to be less influenced by motion than were tasks emphasizing accuracy—an observation consistent with the general finding that vibration has only main effects on reaction time (i.e., motion compared with non-motion) but not frequency- and amplitude-dependent effects (Buckhout, 1964; Grether, 1971b). Finally, it appears that general psychophysiological state variables may have also interacted with task requirements in previous studies. For instance, some data have indicated that tasks that require maintenance of prolonged attention but are otherwise considered tedious or "boring" may benefit from a small degree of imposed vibration, an effect related to a facilitating effect of vibration on the operator's level of arousal (Kjellberg & Wikström, 1985).

3.3 Constraint-Based Design Considerations

Clearly, the relationships between whole-body motion and performance are complex. At the same time, as empirical research proceeds, it becomes increasingly possible to integrate and synthesize the results and observations into heuristics and eventually, formal quantitative models depicting precise relationships among the various constraints that affect the system. As investigation and modeling efforts become more sophisticated, unique and innovative applications are developed that afford compensation for the effects of vehicle motion. A recent approach for compensating motion effects on mobility control (e.g., "vibration breakthrough" or "biodynamic feedthrough") provides a nice example of how recognizing the intrinsic constraints on the system may be beneficial. Rather than working to damp or otherwise eliminate transmission of vehicle motion to the operator, the newly developed method involves recording the vehicle motion, actual disturbances of the operator, and the control input s/he specifies and then uses all this information to subtract unintended input that would normally degrade system performance (Sirouspour & Salcudean, 2003; Sövényi & Gillespie, 2007). Similar examples can be seen in, for instance, adjusting luminance of visual displays to compensate movement-induced reductions in acuity (Griffin & Lewis, 1978) and modifying stiffness of levers and knobs to attenuate the likelihood of erroneous control settings (Lewis & Griffin, 1978; McLeod & Griffin, 1989). Acknowledgment of the need to understand how the Soldier-vehicle system is influenced by multiple sources of constraint may afford opportunities for improvement that have yet to be implemented and tested. That is, rather than following traditional trouble-shooting approaches and attempting to eliminate one set of

constraints to benefit another in a piece-wise manner (e.g., a singular cause-singular solution approach), future designs can recognize and then exploit all constraints as information that may provide insight into improvements that may complement the dynamics of the Soldier-vehicle system as a whole.

4. Applications to Military Vehicles

Given the preponderance of evidence indicating that the experience of vehicle motion is likely to be associated with performance decrements, it is important to discuss potential design modifications to offset undesirable effects without sacrificing survivability or lethality. As with our goal of understanding how vehicle motion influences operator performance, the adoption of a "systems perspective" will allow delineation of variables that may be most amenable to change and manipulation. By identifying such system-sensitive constraints, we enable progress by lending focus to research and development efforts. In particular, after the most influential constraints are known, they can be assessed in terms of how easily and effectively they may be manipulated in the direction needed to improve system performance. Further, rather than attempting to diminish or remove variables that are less amenable to manipulation, we may factor them into the dynamic properties of the system as other, more malleable parameters are optimized for stabilization of performance within acceptable limits of risk and error (Kelso, 1995), even if optimization requires that the variables remain dynamic to accommodate a range of task and environmental circumstances.

In the case of Soldier-vehicle systems, there is clear evidence that each source of constraint (organism, environment, and task) is influential. However, although many of the influential constraints are susceptible to change, not all those that are changeable are also amenable to control. That is, certain variables, such as those relating to the extra-vehicular environment, are highly complex and changeable but are also less controllable from inside the vehicle during execution of a mission or through modifications in vehicle design. Still other variables will be susceptible to change but may simply modify overall system dynamics without actually precipitating improvements in performance. For example, to improve reaching accuracy during vehicle motion, one could vary the inertial properties of the arm by having Soldiers wear lightly weighted armbands. Such a simple manipulation would change the movement dynamics, effectively damp-ing the arm motion and increasing resistance to physical disturbance. However, although this manipulation of organism constraints would most likely reduce the frequency of maximum influ-ence, it would not necessarily remove or attenuate the detrimental effects of vehicle motion. In fact, if we are to trust the evidence that lower frequencies are more susceptible to detriment by increased amplitude of disturbances (Grether, 1971b), then such a change may actually prove counterproductive.

Given the potential for task constraints to exert a broad influence on performance, the remaining discussion focuses primarily on task-level constraints associated with various interfaces between

the driver and the vehicle. The examples we provide are based on lessons learned from the crew integration and automation test bed advanced technology demonstrator program (CAT-ATD) (see figure 1), which were collaboratively conducted through the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate and the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC). Consistent with our argument that efforts must proceed to identify design modifications that complement the constraints imposed on the Soldier-vehicle system, we discuss research and development aimed at optimizing the warfighter-machine interface (WMI); figure 1), which is a human-machine interface that has been developed specifically for implementation in "buttoned up" tactical military vehicles such as the Bradley IFV and the Stryker. The goal of this research was to improve C2 task performance while Soldiers experienced the vehicle motion rather than focusing on how to stabilize or otherwise damp vehicle motion experienced by the operator. Exploiting existing Vetronics Technology Integration (VTI) crew stations, we studied several types of input devices, including those that were already part of the WMI (touch screens, a multifunctional yoke, keyboard with trackball), and other potential input devices including joysticks and speech recognition systems. Functional aspects of these crew stations have been guided by a set of design principles derived from Future Scout and Cavalry System (FSCS), Vetronics test bed, and Warfighter experience (Micro-Analysis and Design, unpublished). General controller design principles included the following:

- Maximize hand contact with the primary steering input device by integration of main mission-critical functions;
- Minimize movement distance to highly used functions that cannot be integrated with the primary steering input device in order to maximize accuracy based on Fitt's Law (Fitts, 1954);
- Accommodate effects of vehicle motion with appropriate touch screen button sizes (Avery et al., 1999);
- Indicate touch events based on button release ("last contact" strategy);
- Maintain multiple interface options sufficient to achieve different task goals across a range of environments.

4.1 Interface Design in Current CAT-ATD Vehicle

The VTI crew stations employed in the CAT-ATD program included three 20.1-inch diagonal (16 in. high by 12 in. wide; portrait orientation) view touch panel displays separated by a 2-inch bezel and a headset. The three panels (Sharp[3] model LQ201U1LW01 color active matrix liquid crystal displays with 1600×1200 resolution) were functionally divided into upper and lower display groups, allowing the operator to simultaneously display three to six separate screens. The screens incorporated a modular design, meaning any function could be placed in any one of the

[3]Sharp is a registered trademark of Sharp Corporation.

screens. For example, the driver could have set the top three functional screens to display external camera views as a virtual windshield while the lower screens displayed vehicle status, mapped routes, and/or other selected information. Each screen was also arranged into a 18.36-inch-diagonal (16-in.-high by 9-in.-wide) readable area with a low-use touch screen and a 16-inch-high by 1.5-inch-wide touch-button strip on either edge of the screen.

Soft buttons were designed to minimize the effects of vehicle motion based on observations during a number of experiments, field tests, and demonstrations. Each button was framed by a 0.25-inch border surrounding an area that allowed a text label of as many as two rows by six columns of characters. Previous observations in pilot studies had suggested that font and icon sizes on the order of 12 points would be practically illegible during stationary and mobile operations. Thus, to improve readability, an Arial 16- or 22-point font, all capital letters, was initially recommended. The Arial 16-point "mixed" font was ultimately adopted and subsequently was reported as readable during moving and stationary operations. This verbal report was supported by observations in tactical military vehicles that indicated a 12-point font was less readable than 14 or 16 point, but there were no differences between the two larger fonts (Tauson et al., no date).

4.2 The Role of Interface Type for Precision Tasks While Soldiers Experienced Vehicle Motion

During the CAT-ATD program, one study was conducted with a map icon placement task to examine three input devices (touch screen, keyboard with embedded trackball, speech recognition system). The placement task was performed while the modified Stryker vehicle was stationary or traversing a prescribed course covering paved roads, secondary roads, or cross-country terrain (Franks, 2003). Four civilian participants individually maneuvered the CAT and were instructed that when they detected a HMMWV, they were to compose a spot report about its location and enter the coordinates as a target on their map. Because the experiment was focused on comparison of interface types, participants were not required to determine the coordinates for themselves, but instead, this information was provided when needed. Results indicated that target entry time while the touch screen was used was fairly consistent across road conditions; mean entry times varied across a 23-second (s) range with an overall average of 56.5 s (see table 3). However, when the trackball was used, entry times were notably longer in the two conditions that induced more vehicle motion (cross-country = 84 s, secondary road = 97 s). When the task was performed in the stationary and paved road conditions, entry times were similar to those observed with the touch screen (51 and 59 s, respectively).

Table 3. Average icon placement time (in seconds) across interface type and vehicle motion condition.

	Road Type			
Interface	**Stationary**	**Paved**	**Cross-Country**	**Secondary**
Touch screen	54	66	63	43
Trackball	51	59	84	97

In addition to timing variables, accuracy was measured as the number of entry errors and the final icon offset distance. The overall error measurement appeared less sensitive to interface type since few input errors were associated with the trackball or the touch screen. The second accuracy measurement, however, was more revealing because of precision constraints involved in the placement of an icon on a grid location on a map. With the touch screen, the offset distance averaged 607 meters (m), nearly double the 345 m observed when participants used the trackball. Although the absolute distance on the screen surface was not provided, this observation indicated that the trackball yielded an advantage over the touch screen for this precision task. Table 4 presents results from errors committed in the spot reports as further validation of this finding. That is, the baseline reduction in accuracy with the touch screen can be seen from data in the stationary condition while the disproportionate increase in errors during vehicle movement validates the argument that reliance on a touch screen exacerbated errors of accuracy during vehicle motion.

Table 4. Average errors per spot report.

	Stationary	**On-the-Move**
Touch screen	0.17	0.60
Trackball	0.00	0.17

Practical attempts to perform map tasks during vehicle motion with the 2002 VTI WMI used in the CAT (TARDEC, 2002) partly complemented these findings. As with the more recent study, input to the maps could be alternately achieved through a touch screen, bump cursor (i.e., an input device that operates in a similar manner as cruise control speed adjust is implemented in civilian automobiles), or keyboard. Similar to the trends indicated by the accuracy results, map manipulation with a touch screen during movement was considered difficult. Further validation of this difficulty was revealed in a 2003 evaluation of the VTI vehicle Phase II WMI review wherein difficulties with a task as simple as drawing a straight line on the map were identified. In fact, the possibility was raised that it may not be possible to draw continuous lines during vehicle motion. However, alternate approaches, such as placing points along a line, which are subsequently interpolated by the computer, may lead to more acceptable performance. More to the point, with its current resolution, the touch screen appears unlikely to be the most desirable interface for tasks requiring any degree of precision. For instance, during a demonstration of the CAT interface, four Soldiers indicated a strong preference when using the trackball for fine manipulation tasks, stating that they found it to be an essential input device. In part, icon placement with the touch screen was not only difficult because of lack of precision in identification of coordinates from the surface area under the point of contact with the finger (i.e., because of the intrinsic organism constraint of fingerprint size), but this difficulty was exacerbated by occlusion of the icon by the operator's finger (illustrating a negative

organism-task-constraint interaction). As a consequence, the trackball was naturally preferred for precision work because it allowed Soldiers to use smaller pointers with greater ease of specifying particular coordinates and with considerably less potential for obscured on-line visual feedback regarding performance.

Following a demonstration of the CAT and robotic vehicles, Soldiers provided a number of additional qualitative comments supporting many of these interpretations regarding design features. While in the moving VTI vehicle, operators executed RSTA (reconnaissance, surveillance, and target acquisition) and target engagement missions and indicated that while "*in motion, all tasks became harder, and some tasks (editing plans and maps, and target acquisition) became virtually impossible under cross-country operations*" (TARDEC, 2002, p. 37). Most operators cited a need for stabilization points for their hands that would allow control over touch screen entry during vehicle motion. One operator successfully "*…add[ed] icons to the map while on the move. He used the touch screen to select which icon and the keyboard to type in the coordinates*" (TARDEC, 2002, p. 34), thus illustrating the potential utility of preserving multiple input options during mobile operations. In general, the touch screen was the preferred interface for most input, but it was acknowledged as difficult to use for precise map manipulation tasks such as icon placement. Some operators reported difficulty using the keyboard during movement because of the lack of physical restraint. Specifically, it was noted that vehicle motion tended to cause the keyboard to bounce on the operator's lap, thus creating an additional task constraint (i.e., not dropping the keyboard and stabilizing it while concurrently using it for input). This latter issue may be accommodated if a stable platform is provided upon which to house the keyboard, perhaps one outfitted in a manner that would damp physical transmission of vehicle motion to the keyboard. Of course, implementing this solution would pose additional nontrivial problems with space claims, potentially requiring the seat to be pushed back farther and thus would modify the reaching distance to the touch screen.

4.3 Optimizing "Soft Buttons" on the Touch Screen for Use During Vehicle Motion

Overall, most input tasks were judged more difficult or impossible during vehicle motion. For example, one operator estimated an 80% increase in workload while mobile. Other comments from in-vehicle experiences stated that "*While moving, everything was more difficult: control inputs on the yoke, watching the screen, placing objects on the map, planning a route, typing on the keyboard, reports, etc ... Even soft buttons were hard to operate ... Target acquisition was hard while moving, since the yoke must be operated precisely. One operator stated that without stopping the vehicle, one couldn't edit a waypoint, move it, or delete it.*" (TARDEC, 2002, p. 37). Again, these qualitative impressions were verified through a series of experiments that demonstrated the detrimental effects of vehicle motion while the vehicle traversed rough terrain. Included in the effects of vehicle motion was an indication of increased difficulty for an operator attempting to activate command buttons (McDowell et al., 2005; Rider et al., 2003). The available data suggested that planning and executing button activation tasks required more time to complete, reaching strategies changed, and reaches were less accurate during motion conditions. In particular, observations indicated that use of the touch screen in a moving vehicle was made considerably

more difficult because the unsupported hands of the operator tended to move as much as 6 inches from their target during moderate to severe vehicle motion.

The CAT-ATD program revealed three potential solutions to improve operator control in button activation during vehicle motion. First, in field testing during vehicle motion, operators were observed grabbing the bezel between the screens, which allowed the operator a point of manual stability (i.e., “anchoring” the hand with the fingers) while he activated the soft buttons with his thumbs. It was suggested that the addition of an environmental support specifically for the hands might improve performance. Some caution is warranted in terms of the specific type of support chosen since a variety of studies has shown that the use of an armrest, for instance, actually increases detrimental effects of vehicle motion by providing a more direct contact between the arm and movements of the vehicle (Lewis & Griffin, 1978; McLeod & Griffin, 1989). Similar concepts could be extended to the suggestion that hard buttons should be used for vehicle and mission-critical functions since their intrinsic stability points and tactile feel allow enhanced performance during vehicle motion. Second, to offset the effects of vehicle motion on reach accuracy, touch screen button dimensions were increased to 1 inch high by 1.5 inches wide with 0.13-inch spacing between buttons, the screen bezel, and the rest of active screen elements (Micro-Analysis and Design, unpublished). Third, buttons were activated by a “last contact” strategy, meaning that if any part of the button was touched when the operator’s finger left the screen, the button was activated. “Last contact” activation was used to allow the operator to correct any error in finger placement before activating a button or touch screen function. Following a demonstration of the CAT and robotic vehicles, Soldiers provided comments supporting many of these design features. The participants reported that it was difficult to control their hands during vehicle motion and that they would appreciate the availability of bars or handles on the sides of the display to anchor their hands; at the same time, the Soldiers verified that the “last contact” strategy allowed them to make corrections before activating a button in error.

4.4 Optimizing Interfaces for Mobility Control Functions and Minimizing Space Claims

Space limitations provide the primary motivation for investigating less traditional input devices (such as joysticks) for vehicle mobility control. However, an additional benefit is that alternate steering input devices afford implementation of steer-by-wire technology that gives control designers more flexibility and options for integration of intelligent automation than do traditional mechanical linkages. Testing in the automotive industry indicates that joystick controllers may be feasible for on-road driving (Chiappero & Back, 2002; Fowler, 2003), but there are significant concerns with how this type of technology will transition to military platforms, particularly when we consider the impact of vehicle motion. For example, it is estimated that a vast majority of military applications will require off-road or cross-country mobility (Bianchi, 2007) that will be associated with shocks and vibrations above those experienced on paved and unpaved roads. The potentially catastrophic consequence of attempting to implement more sensitive steer-by-wire interfaces for vehicles operating in such conditions is that shocks and vibrations can be transmitted through the operator to the control system (a phenomenon known as “vibration breakthrough” or

"biodynamic feedthrough"), leading to a situation in which unintended control input may degrade the vehicle control (Franks et al., 2004; McLeod & Griffin, 1989; Sövényi & Gillespie, 2007). The CAT vehicle used a multi-function, two-handed yoke as the steering input device for driving and teleoperation (see figure 1). When integrated with a mobility control system that could autonomously drive the vehicle (without driver input), the yoke could also be used to control the active display for tasks such as target acquisition, without completely yielding mobility control. In this mode, control of secondary displays required the use of the touch screen. Integration of a bump cursor also allowed an operator who was driving or teleoperating a vehicle to manipulate the cursor without moving his or her hands from the control yoke, thus minimizing potential control degradation because of the effects of vehicle motion on an unsupported arm.

To assess design options for the CAT-ATD, the impact of secondary roads and mild cross-country terrain on slow to moderate speed (< 22 mph) indirect vision driving performance was examined with joystick and yoke steering input devices (Franks, 2004). This study examined performance differences between a yoke and a displacement joystick for steering and secondarily, performance differences between a joystick and pedals for throttle and brake control. Eleven participants completed three conditions including (a) driving with a displacement joystick and pedals, allowing separate control of heading and acceleration; (b) driving with a displacement joystick alone, allowing integrated control of heading and acceleration; and (c) driving with a standard yoke with pedals. Overall, the yoke condition was associated with faster driving speeds and fewer obstacle contacts than the other two conditions. Participants also commented that the yoke provided better stability because it allowed the use of both hands. At the same time, the quantitative results did not indicate a difference in lateral deviations from the desired path among the three conditions, suggesting equivalent heading control capabilities across interfaces. In all conditions, the effects of the throttle on/off technique when the integrated joystick was used during traversal of cross-country terrain revealed that increased speed variability affected the time to complete the course and seemed to contribute to motion sickness. Although this was observed in all configurations, it was most pronounced when the vehicle operated autonomously (i.e., navigated the course without continuous operator input) and when participants had to drive the vehicle via an indirect vision system. Taken together, the observations indicated that the poorer performance with the joysticks may have been attributable to factors other than or in combination with vehicle motion.

On a final but nontrivial note during earlier evaluations of the Bradley IFV-mounted VTI work stations, it was noted that "*The control handle design was rated moderately useful (5.7, 4-7) and relatively easy (5.0, 4-6) to use. There was no force feedback through the control handle since the control system was based on a drive-by-wire mechanism*" (Smyth et al., no date, p. 62). The importance of this note is that to date, there has been relatively little assessment of the inclusion of force feedback to the operator through the steering input devices used for mobility control in tactical military vehicles. However, a variety of studies in other by-wire vehicles (civilian autos, simulators, and aerial vehicles) has indicated that inclusion of force feedback through simple modification of the steering input device stiffness (Lewis & Griffin, 1978; McLeod & Griffin,

1989) or through the use of an active mechanism (Andonian et al., 2003) may be advantageous to mobility control performance, particularly during vehicle motion. This is an important area of research and development for military vehicles that warrants considerably greater attention.

4.5 The Ambiguity of a Relationship Between Motion Sickness and Operator Performance

In a series of studies, ARL and TARDEC examined the effects of sensory mismatch on Soldier performance and motion sickness during simulated vehicle control tasks (Franks, 2004; Hill et al., 2004; McDowell et al., 2008). Across these studies, the general paradigm was to have participants teleoperate one vehicle while riding in a second vehicle, with or without performing secondary tasks such as route planning and communications. The primary experimental parameter was the degree of correlation between the controlled vehicle (visual stimulus) and the occupied vehicle (physical stimulus). Initial analyses indicated that sensory mismatch effects on vehicle control were minimal. Small increases in vehicle speed and lateral deviations occurred when the correlation between the motion of the two vehicles was low as opposed to when the correlation was high. Conversely, incidences of motion sickness were particularly frequent when the correlation between the occupied and controlled vehicle motions was high, indicating the possibility that operators were attempting to reduce motion sickness symptoms by decreasing overall vehicle motion and speed (likely to reduce rapid changes in acceleration). These data were consistent with observations in a study that examined human side effects associated with simulated flight control from a moving ship on smooth seas as opposed to simulated flight control in a stationary environment (Muth & Lawson, 2003). The authors noted decreases in dynamic visual acuity after exposure to the flight simulator aboard the ship, but only negligible symptoms of motion sickness were reported.

In a similar manner, during a demonstration wherein the operator in the CAT vehicle controlled a robotic follower (RF) and the ARL experimental unmanned vehicle (XUV), it was reported that drivers were able to adequately control the XUV or RF using the yoke without considerable impairment from vehicle motion. Moreover, the operators reported that teleoperation was especially difficult when the CAT vehicle was in motion and attributed this difficulty to their tendency to over-steer and as well as to the incidence of motion sickness. Finally, motion sickness was assessed in the HMI (joystick controller) study discussed (Franks, 2004). In that study, one participant dropped out because of motion sickness. Questionnaire data revealed that the symptomology was highest for the condition in which participants drove with a joystick without pedals. While completing a run, two participants asked to stop the vehicle and got out multiple times during this same condition, and both vomited shortly after exiting. Other participants commented that they “felt hot and sweaty” when driving with the joystick without pedals and requested more air conditioning; these participants were also observed taking off layers of clothing. Note that participants and experimenters alike reported that the throttle implementation on the joystick without pedals created very “jerky” vehicle motion. The increased variability in acceleration may have created an environment that induced motion sickness symptoms. As qualitative support for this inference, the participant questionnaires revealed limited symptomology in the other two

driving conditions where acceleration and heading control were accomplished through different interfaces (pedals and yoke or joystick).

Although a variety of the research efforts as discussed has revealed a relationship between the experience of motion sickness and performance decrement, other results suggest that this relation is tenuous and may be poorly understood as it is manifest in military vehicles. For example, during a demonstration of a Soldier's ability to control an armed robot engaged in RSTA missions, evaluators noted that "*The only motion effect mentioned by the Soldiers was when they were attempting to teleoperate a robotic vehicle while the CAT was in motion. Early in their experience they would counter-steer the robotic vehicle when they felt their own vehicle turning. Visual feedback was immediate and they corrected the control of the robotic vehicles without any degradation in mission performance. After approximately three days, the Soldiers overcame this effect*" (Dahn et al., 2003 p. 9-17). In similar fashion, during the VTI RSTA exercise, "*one operator reported motion sickness effects from operating the robot while sitting in a moving vehicle. The reported effects were very slight. The dominant effect of motion was the increased difficulty in operating the controls while bouncing around*" (TARDEC, 2002, p. 37). In essence, these types of observations support the suggestion from earlier in our discussion that even if motion sickness symptoms are induced, their effects on performance are minimal and confined to initial experiences in a transient manner. Perhaps the only reasonable conclusion at the current juncture is that motion sickness is a real consequence of experiencing vehicle motion in tactical military platforms, and various factors including individual susceptibility, the nature of the motion, and task characteristics will interact to determine if and how the symptoms manifest themselves in concurrent performance decrements.

5. Conclusions

The existing research indicates that the experience of whole-body motion while Soldiers are in tactical military vehicles can be expected to degrade Soldier performance of a variety of tasks and through several mechanisms. If a broad "systems perspective" is adopted on the complex inter-relationships among variables influencing effects of vehicle motion, there appears to be potential for considering design and task modifications to optimize performance within the constraints defined by the dynamics of the Soldier-vehicle system. However, reversing performance loss will not be a trivial task. Potential design solutions for the WMI may vary as a function of the type of vehicle motion, the tasks being performed, and the operator, thus requiring the determination of dynamic ranges (as opposed to static values) of display parameters and control settings that accommodate a broader array of task and environmental circumstances. Certain implementations, such as changing physical and graphical properties of the WMI as well as using innovative inter-action solutions (i.e., the "Last Touch" strategy of button activation) have already demonstrated potential for positive influences over performance variables. For other issues, such as detriments

in accuracy with precision tasks, evidence indicates a need to preserve multiple input options for Soldiers to use in response to dynamic changes in their intra-vehicular task environment. Finally, greater attention needs to be given to incorporating task and environmental dynamics into C3I tasks, for example, blending vehicle motion with vehicle control through the use of appropriate force feedback to facilitate driver performance while s/he is operating the primary vehicle or teleoperating an unmanned asset or developing automatic adjustment of screen luminance and/or font sizes to adapt the task environment to different levels of vehicle motion.

Overall, this review has highlighted the importance of adopting a broad view on all sources of influence over the Soldier-vehicle system as well as careful consideration of those sources that are most likely to respond to design modifications in a most effective and cost-efficient manner. Suggestions such as those mentioned throughout this review provide examples of important directions for research and development efforts aimed at improving future tactical military vehicles.

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